Optimal Tune in Ultrasonic Drilling with Body Sensor

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Abstract: An Ultrasonic drilling/coring mechanism (USDC) has been developed for future NASA exploration missions. The USDC will be used to conduct sampling, in-situ analysis and possibly return samples to earth for future tests. Efficient drilling and coring of rock materials has great significance to the success of NASA planetary program. To optimize its performance, the system needs to be tuned as its environment changes.

The load, when drilling and coring a variety of rocks is unpredictable. Furthermore, the work environment on Mars is less known. To ensure the drilling system be always optimal and have the ability to work in a harsh environment, feedback elements are required. Some of these elements are, performance of the drill when loaded, substrate temperatures, and other environment parameters.

Since the load is expected to be continuously changing it will be necessary to be able to finely tune the frequency in a minimum of time to conserve energy and effective life of the system.
To meet this need linear program theory is applied to optimize the tuning process. An optimal search program has been developed and t he experiments show that this optimal tuning program associated with the body sensor and peak detect module can tune the drills in less than two seconds. It has a potential to be used in other applications that need quick real time tuning.

Introduction

An ultrasonic drill mechanism was developed for NASA exploration missions to Mars. The ultrasonic drill is based on an ultrasonic horn that is driven by a piezoelectric stack [2]. To optimize its performance, the drill system needs to be finely turned. Conventionally the drive frequency is preset to the resonant frequency in a generator. The resonant frequency of the transducer, however, varies due to the changes of pre-stress [3], ambience temperature and so on. The work environment on Mars is less known. To ensure the drill system be always optimal and has the ability to work in a harsh environment, feedback elements are required. Some of these elements are, performance of the drill when loaded, substrate temperature or pre-stress of piezoelectric stack, and other environment parameters.

It is known that transducers have the lowest impedance at their resonant frequency, hence highest current occurs. This implies that it is possible to tune transducers to the frequency where it has the greatest current. This has been used in a lot of applications. The disadvantage of this strategy is that the frequency where the greatest current occurs could be the electrical resonant frequency instead of mechanical resonant point of transducer. Although we can carefully choose the output inductor of a generator, such that the electrical and mechanical system are resonant at same frequency, the inductance of the transformer adds complications to the choice of output inductors.

The body sensor, as part of the mechanical system, has better representation of transducer. This paper will present how this novel technique is used for transducer tuning.

Section 1   Body Sensor

The body sensor is a set of piezoelectric ceramics mounted in the piezoelectric stack of the drill as shown in Figure 1. The sensor ceramics is electrically isolated to rest ceramics, which is used to drive the horn and will be nominated as drive ceramics in rest of this paper The sensors are made of PZT-8 material with ID/OD dimensions the same as the drive ceramics except much thinner. Sensor ceramics is part of the stack and is sandwiched between the drive ceramics and the back mass. The drive ceramics thickness will increase or decrease when an alternate voltage applies to them and hence a stress is applied to the sensor ceramics. As a result, the sensor ceramics will produce a voltage. The voltage amplitude is proportional to the displacement of the drive ceramic. When the transducer is activated with the resonant frequency signal, the displacement of transducer is maximum at this frequency.
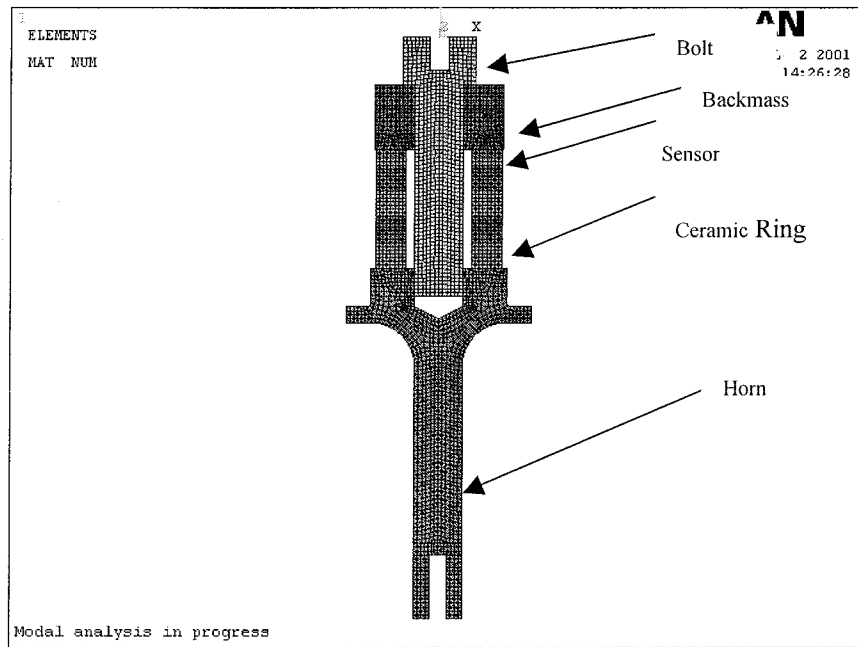
Figure 1 Ultrasonic Drill with Body Sensor

The best way to track the change in the resonant frequency of the system is by activating the transducer with different frequency signals and then registering the peak voltage produced in the sensor ceramics. The frequency that produces the maximum displacement hence the voltage from sensor ceramics is the resonant frequency of the system.

Tests were conduced to prove this principle on the transducer stack. Figure 2 shows the peak-to-peak voltage from body sensor and the tip displacement of the drill measured with Pillitec. The test results showed that the maximum tip displacement of the transducer was corresponding to the frequency that produced the most voltage in the sensors. The drilling performance is directly

proportional to the tip displacement, and could therefore, be related to the maximum voltage generated in the sensors.

Section 2   Peak detect Circuitry

In order to track the resonant frequency, the amplitude of the voltage produced by sensor ceramics needs to be compared at each frequency. Figure 3 is a simple peak detecting circuit [4].
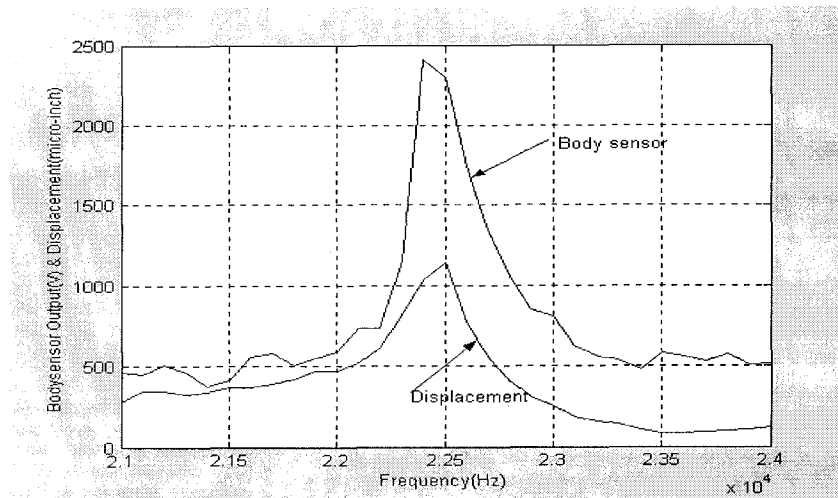

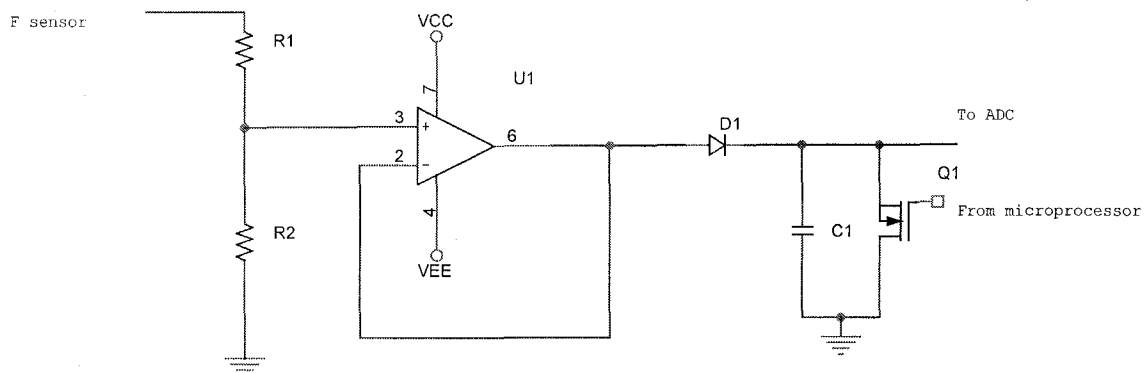Figure 2. Measured Tip Displacement and Body Sensor Output

Figure 3 Peak Detect Circuit

Section 3   Underline Principle of Optimal Search Method

There is a fundamental underlying structure for most optimal algorithms [1]. One starts at an initial point; determines, according to a fixed rule, a direction of movement; and then moves in that direction to an extremum of the objective function on that line. At the new point a new direction is determined and the process is repeated. The primary differences between algorithms

rest with the rule by which successive directions of movement are selected. Once the selection is made, all algorithms call for movement to the extremum point on the corresponding line. In this section a few possibilities are outlined and analyzed.

Since there is a clear peak at resonant frequency in Figure 2. It is easy to sweep through a range of frequencies and poll the A/D converter for the voltage level across the sensor ceramics. This is a slow procedure, however. To increase the resolution of the sweep and to reduce the time in the sweeping process, the first sweep was set up to broad range (2kHz) in large increments, 100Hz for instance. Then the narrower sweep was used based on the results from the broad sweep to vary +/- 200 Hz of the determined resonate frequency at 20 Hz increments. The later approach is in some sense is optimal. It, however, is still slow.

By noticing that there is only one significant peak near resonant point, it can be safely assumed that the function being searched being unimodal, possesses a certain degree of smoothness, and one might, therefore, expect that more efficient search techniques exploiting this smoothness can be devised. Techniques of this nature are usually based on curve fitting procedures where a smooth curve is passed through the previously measured points in order to estimate of extremum point. A variety of such techniques had developed depending on whether or not derivatives of the function as well as the values can be measured, how many previous point are used to determine the fit, and the criterion used to determine the fit [1].

Since there is no real time measurements of derivatives, quadratic fit is applied here. This scheme has the advantage of not requiring any derivative information.

Give x_1, x_2, x_3 and corresponding measurements y_1, y_2, y_3, we construct the quadratic passing through these points,

$$q(x) = \sum_{i=1}^{3} y_i \frac{\prod_{j \neq i}(x - x_j)}{\prod_{j \neq i}(x_i - x_j)}$$

and determine a new point x_4 as the point where the derivative of q vanishes. Thus

$$x_4 = \frac{1}{2} \frac{b_{23}y_1 + b_{31}y_2 + b_{12}y_3}{a_{23}y_1 + a_{31}y_2 + a_{12}y_3} \tag{1}$$

where $a_{ij} = x_i - x_j, b_{ii} = x_i^2 - x_j^2$

If, however, we apply this technique directly, there is the possibility that the process would diverge or wander about meaningless. In other words, the process may never get close enough to the solution. The key to guaranteeing converge is to find three points, such that a quadratic fit these points will have a maximum.

It has been discussed that the body sensor output versus frequency has a peek. We can initiate our search procedure by searching along the line until we find three points x_1, x_2, x_3 with $x_1 < x_2 < x_3$ such that $y_1 \leq y_2 \geq y_3$. This pattern will have a maximum and the maximum

point will lie in the interval $\left[x_1, x_3\right]$. The way to find such sequence points will be discussed in next section.

Section 4. Real-Time Implementation Issues and Experimental Results

We had analyzed the optimal search method. This strategy is under assumption that the curve of body sensor output versus frequency is smooth and unimodal. In practice, however, the measurements are noisy, hence the curve can never be smooth. Furthermore, it may have more than one local maxima due to characteristics of transducer or noise as shown in Figure 4. It is possible to reach a local maximum instead of global one. Some of real-time implementation issues will be discussed in this section.
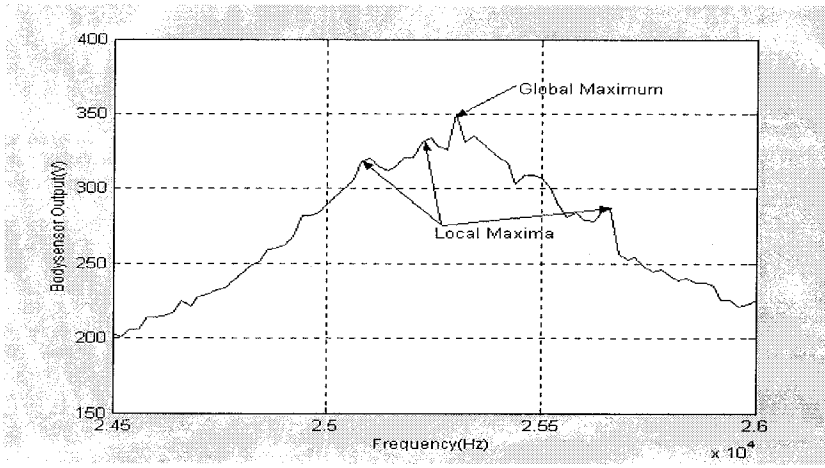

Figure 4. Body Sensor Output from Thrombo Transducer

The capacitor C1 in Figure 3 needs to be carefully chosen in order to reduce the noise. A large capacitor can significantly reduce noise, but may not fast enough to represented change of the voltage from body sensor output. A digital filter has been implemented to reduce measurement noise, which averages 10 measurements at each fixed frequency. The frequency of the drive signal was generated from a microprocessor controlled frequency synthesizer following by a phase lock loop. This allows us set drive signal to any frequency between 15kHz to 37kHz.

It has been discussed in last section, to ensure the search converge to resonant point, it is necessary to find three point f_1, f_0, f_2 that satisfied:

$$v(f_1) \le v(f_0) \ge v(f_2)$$

where $v(f_1), v(f_0), v(f_2)$, are the measurements at frequency equal to f_1, f_0, f_2 respectively.

Without lose generality, assuming that we know the resonant point is in $\left\lfloor f_1, f_2 \right\rfloor$, we can start at any frequency f_0, through a series of halvings and doublings of f_0 and comparing the corresponding $v(f_0)$ with $v(f_1)$ and $v(f_2)$, a three-point pattern can be determined.

In practice, it is possible to calculate the resonant frequency according to the mechanical characteristics of a transducer. We can initial f_0 equals the calculated resonant frequency, then let

$$f_1 = f_0 - \Delta f$$
$$f_2 = f_0 + \Delta f$$

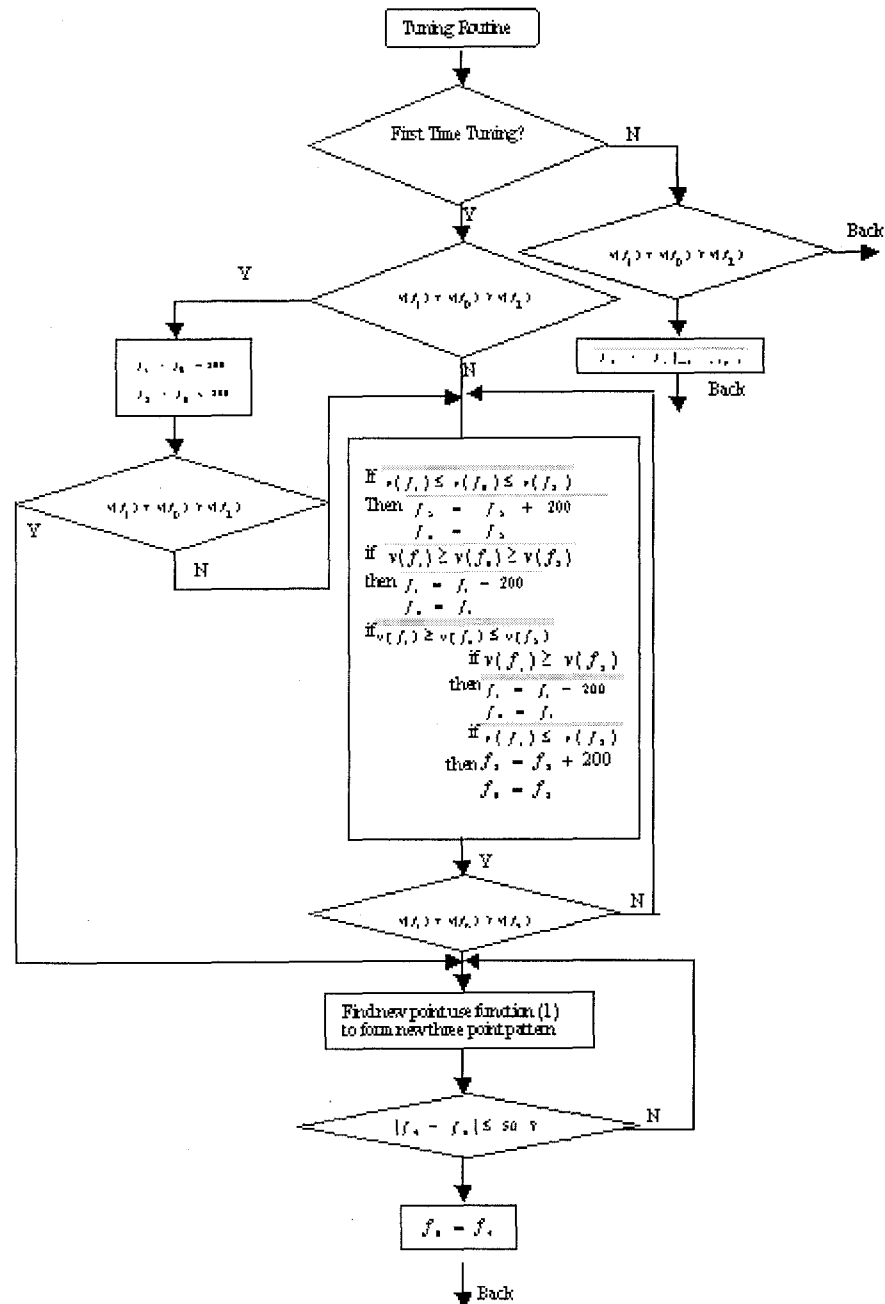Δf should be chosen as small as possible as long as the three point pattern is still most likely

Figure 5. Flow Chart

exist. In other words, the narrower bandwidth, the smaller Δf is. Here in our drill application, Δf is 100. To avoid staying a local maximum, other two points at $f_0 - 2\Delta f$ and $f_0 + 2\Delta f$ are also compared to at f_0. Figure 5 is the flow chart of tuning routine. In case of that f_0 is chosen too far away from resonant point, so that the three-point pattern does not exist, a process as shown in Figure 5 will be repeated till three-point pattern is found.

Since the resonant frequency only changes around the resonant frequency at most operating condition, it may not necessary to go through the tuning entire process each time. Once the transducer is tuned, we can only compare three points at f_0, $f_0 - \Delta f$ and $f_0 + \Delta f$. Then the frequency at which the output voltage of body sensor is largest will be the new operating frequency. Again Δf is depends on the bandwidth of the transducer.

Section 5 Conclusions

A feedback mechanism so called body sensor has been introduced in this paper. An optimal tuning procedure using body sensor has been discussed. Real-time implementation issues were addressed. The experimental results show that body sensor output is consistent with the displacement of transducers. By using an optimal search method, the tuning process takes less than two seconds. Since resonant frequency only changes around the original point, the three points comparison method makes the tuning even faster. The technique presented in this paper allows for quicker and more accurate tuning. It has also been used in medical instrument tuning and has the potential to be used for industrial applications.

Acknowledgment

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